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SwellFit: a Wearable Sensor for Patients with Congestive Heart Failure

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Abstract

Congestive heart failure (CHF) is the most common reason for hospitalization in people aged 65 years and older in the United States. Especially, a very high rate of unplanned readmissions within 30 days of discharge due to CHF occurs a heavy associated financial burden and degraded quality of care. To effectively prevent CHF readmission and improve overall care, this paper proposes SwellFit, a novel wearable sensor that helps outpatients to proactively monitor a physical symptom of worsening CHF, ankle swelling. Using a flex sensor, SwellFit monitors changes in ankle curvature as an indication of swelling. A pilot test with 4 adults showed that SwellFit successfully distinguish noise data and motion artifacts from ankle swelling. Collaborating with cardiac experts, we are currently planning to test SwellFit with hospitalized CHF patients who have swelling conditions to demonstrate the feasibility and reliability of SwellFit on detecting swelling from ankle curvature.

Author Keywords

Congestive heart failure, heart failure, chronic care, mobile device, self-monitoring, wearable technology

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

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Introduction

Congestive heart failure (CHF) is a chronic condition in which the heart is unable to pump sufficiently to maintain blood flow to meet the body's needs. Its physical symptoms include shortness of breath, fatigue, swollen legs, and rapid heartbeat. While all conditions of CHF cannot be reversed, treatments such as medications and lifestyle modifications can improve the symptoms.

Nearly 6 million Americans suffer from CHF. As the most common diagnosis in patients 65 and older in the United States, CHF is known as a leading cause of hospitalization and readmission: close to 1 million hospitalizations for CHF occur annually [7], and more than 25 percent of patients hospitalized for CHF are readmitted to the hospital within 30 days of discharge [9]. Such high rates of hospitalization and readmission result in a huge hospital cost and degraded quality of care [11]. Thus, improved management of the condition is needed to reduce morbidity and mortality, as well as to lower the costs of treatment associated with CHF.

To cope with the huge medical and financial burden caused by CHF, researchers and medical practitioners have sought ways to prevent rehospitalization of CHF patients. A common approach has been to teach and support outpatients to engage in self-monitoring, which involves self-weighing, monitoring of symptoms, and the interpretation of changes in weight and symptoms. In this paper, we propose a complementary approach to support self-monitoring using a personal wearable sensor, SwellFit. This novel wearable sensor helps patients to proactively monitor a physical sign of worsening CHF, ankle swelling.

A pilot test with 4 adults showed that SwellFit successfully distinguished noise data and motion artifacts from ankle curvature values. We are currently collaborating with cardiac experts to plan testing SwellFit with hospitalized CHF patients who have swelling conditions to demonstrate the reliability of CHF on detecting swelling from changes in ankle curvature. We are hopeful that our system could result in reduced readmission rates and enhanced self-care practices of CHF.

Existing practices for preventive care

Diverse interventions have been proposed and are being operated to prevent readmissions of CHF patients. Two prevalent interventions are phone-based remote monitoring and in-home telemonitoring.

Phone-based remote monitoring

The most common effort to prevent CHF readmission is through regular structured telephone contacts between patients and healthcare providers. To structure phone-based remote monitoring, several strategies have been proposed, including transitional care interventions [12], post-discharge care plans [10], and intensive remote nursing care [15]. Studies have shown that that nurse-directed phone-based interventions can reduce readmission rates and length of hospital stay in CHF patients [14]. However, this intervention relies heavily on patients' manual measuring and monitoring of their conditions. Thus, it could lose reliability if patients are not cooperative or lack self-monitoring skills.

Automatic telemonitoring

A number of automatic telemonitoring systems have been developed to support distant monitoring of CHF [5]. These systems consisted of electronic equipment that patients



Figure 1. Final SwellFit implementation. Its form factor is similar to a sweatband.

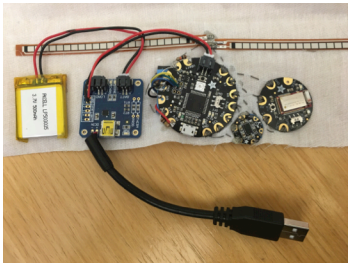


Figure 2. SwellFit parts consist of two flex sensors, a Flora wearable electronic platform, a Flora wearable Bluetooth module, a Flora wearable accelerometer, a battery charging station, and a battery. Parts were connected using conductive thread on a fabric substrate to create a flexible wearable that would not interfere with the flex sensor's range of motion.

use to enter their symptoms and relevant biomarkers such as weight, blood pressure, and heart rate [e.g., 3, 4, 6]. For example, a home monitoring system that measures weight on a daily basis was found to reduce the length of CHF patients' stay at the hospital [2]. CARDIAC is an intelligent conversational assistant that provides distant CHF monitoring through [8]. Alluhaidan also introduced an mHealth system to automatically monitor CHF patients' condition from distance [1].

This approach has advanced phone-based remote monitoring by enabling automatic data transfer from patients to care providers. However, it still requires patients to manually measure or to enter biomarkers to the system, which could involve human errors. Furthermore, most data are not continuously monitored but measured periodically (once a day or less often) so that it could fail to capture critical signs of worsening CHF that might happen in between measures. To cope with this problem and further enhance self-management of CHF, we aim to design a wearable device that continuously monitors CHF patients' condition and inform them early enough when a sign of worsening CHF is detected.

Proposed system: SwellFit

Our goal was to create a wearable sensor that can monitor a physical symptom associated with worsening CHF with minimal effort required of patients. One early physical sign of worsening CHF is swelling of the lower body. Due to reduced blood, fluid accumulates in the lower part of the body, which causes swelling (and edema later on). Currently, there is no systematic mechanism to monitor swelling, except a simple visual checkup or measuring the diameter of an ankle using a tape measure. We focused on ankle swelling, because

modern sensing technologies can easily detect a very small change in ankle swelling by monitoring changes in an ankle curvature.

Measuring ankle curvature for swelling has several advantages compared to measuring ankle diameter. First, to measure diameter accurately, a person has to measure at the exact same location of an ankle every time (intra-rater reliability). Second, manual measuring of an ankle diameter could be different from a person who measures it (inter-rater variability). In contrast, continuous monitoring of an ankle's curvature allows us to detect swelling regardless of the location of measurement without a measurer, as it continuously compares changes in the ankle curvature with previous values in real time.

To that end, we implemented SwellFit, a personal, non-obtrusive, wearable sensor that monitors ankle swelling by measuring an ankles curvature (See Figure 1). Our proposed system enables continuous, more accurate, less variable, and more sensitive measurement of ankle swelling with minimal efforts from patients compared to traditional measurements.

System development

Our system consists of three parts: a hardware sensing platform, software with a backend database for storing and visualizing data, and signal processing to translate flex sensor values to swelling. (See Figure 2)

Hardware

SwellFit hardware comprises of five components; two flex sensors, an accelerometer, a microcontroller, a bluetooth LE module, and a battery with a battery charging station (See Figure 2). The flex sensor detects bending in a direction: as a flex sensor is bent, its

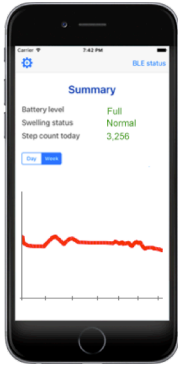


Figure 4. Data Visualization on an iPod Touch.

resistance changes from 10kw to about 20kw, and our system monitors this resistance change. Two flex sensors are connected to wrap completely around an ankle, using a voltage divider with a 10kw reference. The output of flex sensors is sampled at 200Hz and the average value is recorded every second, resulting in an effective 1Hz sampling rate.

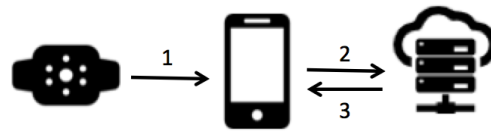


Figure 3: Data transfer between parts: From left to right, SwellFit hardware, an iPod Touch, and a webserver. First, sensor readings from SwellFit are transferred to an iPod Touch via Bluetooth. Then, an iPod Touch sends the data to a server for signal processing through Wi-Fi. Finally, an iPod Touch receives the processed data for visualization from the server.

Additionally, we used an accelerometer to sample acceleration of the ankle at 4Hz (the minimum frequency to detect steps) [13]. The magnitude of the acceleration was calculated using the three-dimensional Pythagoras' theorem. Lastly, a Bluetooth Low Energy module was used to transmit sensor readings from the microcontroller to an iPod Touch. Data to transmit consist of timestamp, raw flex-sensor value, detected step (1 or 0) from an accelerometer, and battery value.

Software

As soon as an iPod Touch receives data from the hardware part, it sends the data to a web server for signal processing via Wi-Fi (to be described in the next section). Swelling values are then sent back to an iPod Touch to render changes in ankle swelling as a graph using Swift (See Figure 4). When the system

determines abnormal swelling, it prompts a push notification. In addition, the iPod Touch also renders step counts to provide a user's activity levels.

Signal processing

As soon as the web server receives new data, it starts processing the data using a Python script as following.

First, to remove noise and to distinguish motion artifacts from actual swelling, we smooth the data using a moving average filter. We evaluated several window sizes for moving average in order to reduce noise without overly smoothing the data. For each window size N from $2 \cdot f_s$ to $14 \cdot f_s$ with f_s (Frequency of sampling) being 1Hz (a sampling rate), we calculated the moving average as a vector. Then, we calculated the difference between the raw sensor values and each one of the vectors. Lastly, we took a first order difference of the means of the difference (the unnormalized error) to find the index (i) of the first value below a threshold. We selected $N = i - k$ where N is greater than 0. Through the evaluation, we found $k = 3$ to be the best. (See Figure 5)

Next, to classify the smoothed flex sensor data into four categories (normal, false negative, swelling, and false positive), we used k-Means as an unsupervised clustering method. We first defined the error vector as the normalized error between the raw data and the smoothed data. Using this error vector, we created a two-dimensional scatter, the smoothed sensor (normal or swelling) data vs. errors (false positive or false negative). We defined each data in four quadrants as follow:

- Normal: High Sensor Value, Low Error

- False Negative: High Sensor Value, High Error
- Swelling: Low Sensor Value, Low Error
- False Positive: Low Sensor Value, High Error

Using K-means with a K of 4, we separated the four clusters for real-time classification. Through this process, we obtained a smoothed sensor value, its classification (whether or not swelling), and a confidence level based on the error vector.

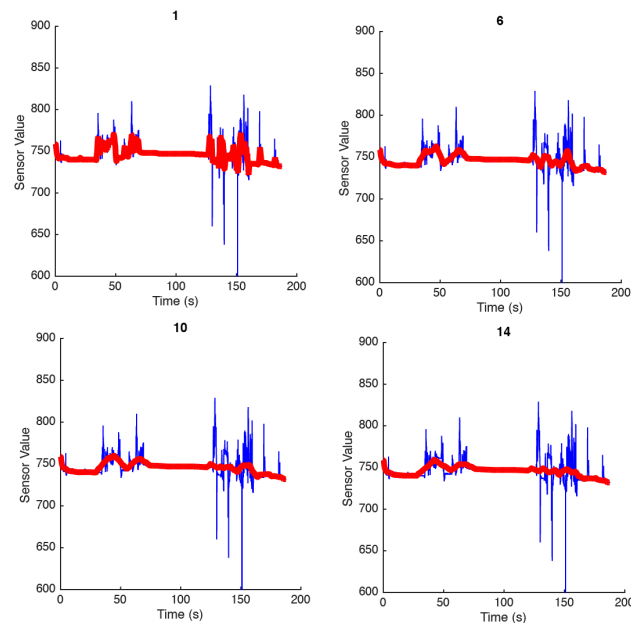


Figure 5: Raw sample flex data (blue line) and smoothed data (red line) with $N = 1, 6, 14$, and 10 from top-left corner clockwise. We found $N=10$ to be the best window size to reduce noise without overly smoothing the data. In this dataset, we identified two “bumps” at 50 secs and

150 secs that were caused by motion artifacts as these were classified as a false negative. There is a slight low, downward trend between the two bumps, which our classifier determines as mild swelling.

Preliminary results

We pilot tested SwellFit with 4 adults for 4 days. Our pilot study demonstrated that SwellFit adequately performed its data logging abilities. Also, SwellFit was robust enough to daily activities (including exercise, bicycling). Wearing it did not cause discomfort due to warmth or constriction and the sensor was robust enough to rotational force.

The signal-processed data demonstrated that SwellFit successfully differentiates swelling from motion artifacts (e.g., change in values caused by sensor rotation, external force, etc.). The classification of data using the k-Means algorithm allowed SwellFit to identify when abnormal swelling happened.

Conclusion and future work

Congestive heart failure is a chronic condition that causes a significant medical and economic burden to both patients and the society. As part of the efforts to reduce unplanned readmission rates caused by CHF and to enhance self-management of CHF care, we designed SwellFit, a personal, non-obtrusive, wearable sensor that monitors ankle swelling. A pilot test with 4 adults showed that SwellFit successfully distinguishes noise data and motion artifacts from ankle swelling.

Collaborating with cardiac experts, we are currently planning to test SwellFit with hospitalized CHF patients who have swelling conditions to demonstrate the feasibility and reliability of SwellFit of detecting swelling from ankle curvature. Once we validate the reliability and the feasibility of SwellFit, we will deploy it to CHF

patients and evaluate its usefulness in real-world settings. We are hopeful that the successful development and deployment of SwellFit will help prevent unplanned readmission rates caused by CHF and enhance self-management of CHF.

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